Zero-net energy management for the monitoring and control of smart water systems[☆]

Carlo Giudicianni[a,*], Manuel Herrera[b], Armando di Nardo[a], Armando Carravetta[c], Helena M. Ramos[d], Kemi Adeyeye[e]

[a]*Department of Engineering, Università degli Studi della Campania 'L. Vanvitelli', via Roma 29, Aversa 81031, Italy*
[b]*Institute for Manufacturing – Department of Engineering, University of Cambridge, 17 Charles Babbage Rd., CB3 0FS Cambridge, United Kingdom*
[c]*Department of Hydraulic, Geotechnical and Environmental Engineering, Università di Napoli Federico II, via Claudio, 21, Napoli 80125, Italy*
[d]*Civil Engineering, Architecture and Georesources Department, CERIS, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal*
[e]*Department of Architecture and Civil Engineering, University of Bath, Claverton Down, BA2 7AZ Bath, United Kingdom*

Abstract

This paper proposes a novel adaptive management framework for water distribution systems (WDSs) based on the reconfiguration of the original network layout into (dynamic) district metered areas (DMAs). It was found that although there is the overall decrease of energy for partitioned WDSs, there is local augment on the water velocity at the boundary pipes between DMAs. This offered the potential to recover energy from the system in combination with the improved monitoring and control, commonly associated with a WDS management by DMAs. To achieve this multiple objective, a multiscale clustering algorithm is proposed to schedule DMAs aggregation / desegregation, whilst delivering energy and supply management goals. The proposed framework was tested in a utility network for the simultaneously production of energy during the day (by means of the installation of micro-hydropower systems) and for the reduction of water leakage during the night. A recovered energy potential of 19

[☆]This study is in collaboration with the Reducing Energy Dependencies in Water Networks REDAWN project which is partially funded by the EU Interreg Atlantic Area, and the Water Efficiency Network.

[*]Corresponding author
Email address: `carlo.giudicianni@unicampania.it` (Carlo Giudicianni)

MWh per year and leakage reduction of up to 16% was found. The financial analyses to define the optimal period in which to invest also showed the economical feasibility of the proposed solution which assures a positive annual net income in just five years. The combined optimisation, energy recovery and creation of multiple-task stations therefore led to an efficient, resilient, sustainable, and low-cost management strategy for the WDS.

Keywords: Water distribution systems, micro-hydropower systems, sustainable and smart cities, recovered energy, water leakage reduction, financial analysis

---

1. Introduction

More than half of the world's current population live in cities. A growth of 1,500 million people in the last 20 years. The United Nations predicts that this trend will continue; it is expected that up to 6.5 billion people will be living in cities by 2050. Climate change impact on society will be increasingly connected to weather-driven hazards because extreme weather are expected to disproportionately rise compared with changes in climate averages [1] . Conversely, cities are a main actor in climate change. Buildings consume 20%-40% of the world's energy and account for up to 40% of global greenhouse gas emissions. The associated energy to the water system worldwide was 120 Mtoe in 2014, mainly in the form of electricity, corresponding to 4% of the total global electricity consumption [2]. In particular, water distribution represents the largest share of energy consumption in the sector [3]. Apart from environmental issues related to the rational use of energy, the persistent increase of the energy tariffs directly affects the water costs. The necessary use of new technologies and their associated cyber-physical systems (CPSs) to manage assets such as sensors that gather and analyse data across a smart city, further increases the use of energy.

1.1. Motivation

The efficient management of water systems, in terms of energy and resource, thus, represents a crucial task towards a more sustainable use of water. Further, the energy potential in water networks can also be used to deliver social good especially in peri-urban and rural areas where energy infrastructure may be costly or lacking [4]. Previous studies of micro hydropower [5] have demonstrated the comparative social value of renewable schemes, in addition to financial and environmental value.

Furthermore, water distribution systems (WDSs) represent critical infrastructure, that support economic prosperity and human life, and whose malfunction can have great impact on the quality of life. The United Nations Sustainable Development Goals (especially Goal 6, 11 and 12) define actions aiming to ensure improved access to safe water, improved resource efficiency in water systems through sustainable consumption patterns [6]. On the other hand, WDSs are large-scale, complex, and dynamic systems [7], the efficient and effective management of which still represents an arduous task for water utility managers. Indeed, in addition to supplying water to the users and satisfying the minimum service level, the main goals for water utilities nowadays range from managing abnormal conditions (such as burst pipe scenarios, peak demand variability) to dealing, at near real-time, with accidental or intentional contamination [8], cyber-attacks [9], optimal sensor station placement [10], and leakage detection [11]. As cities grow, water systems are becoming larger and more complex interconnected networks which is not trivial to manage management. Thus, the management of water distributions systems to satisfy user water needs with respect to the sustainable environmental and financial considerations, and within affordable energy costs.

Nowadays, the realisation of smart water systems solutions with improved efficiency, longevity, and reliability of WDSs by better measuring, collecting, analysing and acting upon a wide range of system events, is imperative. This can takes shape in different phases of the utility process, such as real-time monitoring and automation, operational readiness, or network planning, leading to system efciency in the integrated water-energy frameworks. In this regard, smart actions devoted to safe/ energy recovery and leakage reduction contribute to reductions in cost and the environmental impact associated with the operation, whilst contributing to the diversication of electric energy production. To this aim, the optimal positioning and setting of micro-hydropower system [12], is combined with the optimisation strategy of the water network partitioning to deliver a pro-active, efficient and cost-effective management of WDSs. The need for this holistic approach to create sustainable systems was strongly highlighted in [13].

1.2. Literature survey

One of the main challenges of the water companies is how to minimise water losses and wastage of finite water resources and whilst protecting the natural environment and its ecosystems. Pressure management, among others, represents a proactive measure to reduce water loss in WDSs [14]. Pressure Reducing Valves (PRVs) are used to reduce pressure to the minimum level whilst maximising the service level to meet consumer demands, pressure-reducing valves are used for this purpose [15]. The challenge is the definition of the optimal location, and the number of pressure control elements and settings in WDS to minimise leakage and simultaneously satisfy the minimum service level, by minimising the investment cost [16]. Water network partitioning (WNP) helps to meet this challenge for the pressure management. WNP is the process of splitting a water distribution system into a set of independent district metered areas (DMAs) [17]. In addition to providing an overall head drop which leads to a reduction in water losses, leakage can be more easily quantified in each DMA by measuring minimum night flows [18]. The leakage is assumed to be the difference between the minimum night flow and the customers' night consumption. Anyway, it is important to highlight that, the design of permanent DMAs (with the insertion of gate-valves) could significantly reduce the head pressure over the WDS and, consequently, the energy resilience. Therefore, the optimal WNP design always represents an arduous task for the water utilities which must limit the alteration of the hydraulic performance. This is the reason why, normally, WNP is not specifically tailored for the water leakage reduction, but this aspect is considered as a secondary advantage to exploit during the night, when the request and variability of water demand strongly reduce, pressure reaches higher values, and lower values of energy resilience are acceptable.

WNP has become one of the most attractive and studied strategy for the improvement of WDS management. DMAs are formed in WDNs by placing gate valves along some boundary pipes connecting one DMA to another and placing a flow meter in the remaining connecting pipes (Figure 1). Over the years, working with DMAs has helped water utilities to simplify water balance computation [19], carry out leakage control [20], [21] pressure management and hydraulic performance [17], monitor water quality [22], and speed up repairing interventions [23]. In this way, water utilities can easily and efficiently plan management programs and compare the overall WDS performance between DMAs, by reducing the complexity of the network layout into smaller monitored areas.

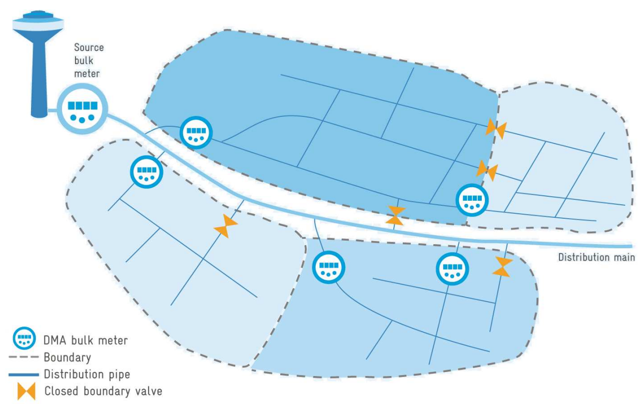


Figure 1: Water Network Partitioning

Although working with DMAs has of the fore-described advantages, it comes with important associated inconveniences. As mentioned above, these are mainly related to the energy efficiency for supply and water quality. Partitioning of WDNs could lead also to a significant reduction of the redundancy of the network and the overall system resilience, especially in the case of non-contemplated functioning conditions [24]. In fact, traditionally, WNP is a static solution for urban water distribution operation and management. Therefore, a dynamic/adaptive approach to WNP represents a valid and efficient solution for dealing with these drawbacks, allowing to simultaneously meet different management goals. The advantageous of an adaptive WNP were highlighted by [25, 26], but these works fall short of providing a methodological approach to deliver it.

Further, in the last years, several studies have been carried out also to develop alternatives to reducing energy consumption in the water sector [27]. In this regard, pressure control represents an important issue for energy efficiency improvement, reducing both the energy consumed in pumping station and the pipe leakage (which also reduces energy consumption indirectly owing to the reduction of the total flow). Indeed, the water and energy efficiency can be improved through the diminishing of head losses, the reduction of the flow consumption in gravity pipes systems, as well as the reduction of the pressure and consequently the leakages in the water distribution systems [28, 29, 30]. Thus the use of pumps working as turbines (PATs), as an alternative solution to reduce the pressure in pipe systems by replacing or in conjunction with the pressure reduction valves, was proposed by [31]. This recovery system has the advantage of pressure control regulation and in addition to energy generation. This renewable system, can lead to the improvement of the future sustainability of the WDS [32]. Hence, in water systems with excess energy, it is possible to install PATs which produce electric energy from the available excess of hydraulic energy, which would normally be dissipated through the PRV.

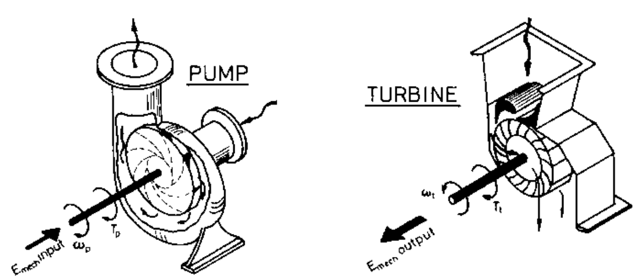


Figure 2: Difference between Pump and Pump as Turbine

The main concept is that, the pump converts mechanical energy of impeller into pressure and kinetic energy of water. Whilst when the pump works in reverse mode, it converts pressure and kinetic energy of water into mechanical energy of the runner (Figure 2).

Indeed, in WDSs, and in particular in the transmission pipelines, hydraulic power is larger and relatively constant, turning transmission pipelines into potential energy sources (Figure 3). The knowledge of power availability is an essential factor to predict and define the economic benefits of converting energy dissipation into energy production [33].

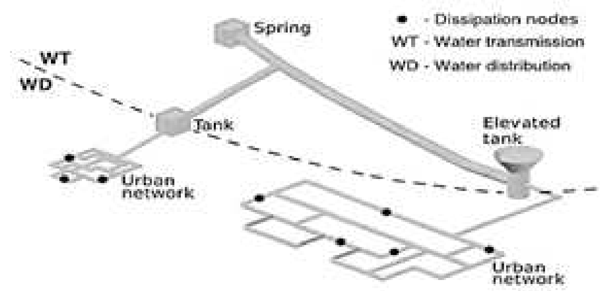


Figure 3: Water Distribution System

Pumps as Turbines represent a viable solution for electric energy production thanks to low maintenance, investment and repairing costs, and good efficiency. Furthermore, PATs are a clean source of energy, with low environmental impacts, representing an alternative opportunity to control pressure in WDSs also increasing the flexibility of the system [34].

1.3. Contributions

Given these current and future scenarios, the current paper is aligned with the research on smart and resilient cities [35, 36], aimed at an efficient urban water supply from points of view: To capture the energy generated during water distribution whilst controlling and monitoring leakage. This is possible thanks to an efficient WNP management and the potential for energy recovery from the boundary pipes between the DMAs. These are shown to be the points where kinetic energy increases even when the overall WDS energy decreases when combined with network partitioning. In fact, the lower number of connection between districts causes a higher value of the water conveyed along them (and as a consequence of the velocity). This concept proposal pioneers an automated and practical approach to effectively achieve the dynamic water network partitioning (DWNP) related to an adaptive DMA configuration. The proposed research develops a generic framework for the dynamic top-down / bottom-up partitioning of WDSs for a smart, efficient and sustainable management in response to different goals, by saving energy (and CO_2 emissions), water and costs. This is achieved by a novel multiscale abstraction of the original water network layout [37] on which the clustering algorithm (that takes into account at each step the previous DMA layout), is applied. Consequently, DMAs are dynamically:

- *aggregated*: into bigger areas during the day (when the water flows reach higher values), to assure the network resilience and to recover energy; and periodically
- *desegregated*: during the night (when pressure heads assume higher values) for a better detection and reduction of leakages.

Thus, the disadvantages of a closed topology are significantly reduced without losing the possibility to exploit the strengths of the water network partitioning. From a computational point of view, the proposed framework assures a strong reduction of the time and complexity, both during the clustering phase (working on the reduced MS network layout) and during the dividing phase (defining a sub-set of the boundary pipes to optimise at each level of the management). Another innovative aspect of this paper is the installation, along the boundary pipes, on the same monitoring station, of flow-meters as well as micro-PATs. This leads to a reduction in both the investment and maintenance costs, a simplification of the management, and an automation of the monitoring (electrical devices with power directly supplied from the recovered energy).

This last aspect gives improved reliability to the monitoring stations, since they keep working in case of any failure of the local power grids. Finally, a simplified decision support system is proposed to help define the optimal period for investment and implementation decisions.

1.4. Organisation of the paper

This paper is organised into five main chapters. In the first section, the WDS challenges are contextualised followed by a literature review about the management strategy of the water network partitioning and the installation of micro-PATs. In Section 2, the dynamic/adaptive framework for the zero-net energy management of WDS is technically and mathematically described. In Section 3, the principles are tested on a real case study, followed by the results in Section 4, and the discussion of the main advantages of the work in Section 5. The final section of the paper presents the conclusions and future work.

2. Methodology

This section introduces the process for dynamic/adaptive water network partitioning. This is approached through the novel concept of multiscale (MS) water network layout, which is shown to be useful for automating the creation of dynamic DMA by a semi-supervised MS clustering, according to the variability of the function conditioning in the WDS.

2.1. Semi-supervised multiscale clustering.

The novel concept of multiscale (MS) water network layout, is shown to be tailored for automating the dynamic process by a semi-supervised MS clustering. It is based on the extraction of key elements from the original layout:

- *boundary node*: landmark nodes acting as inlet / outlet of a partitioned network;
- *hyper-links*:

  - *boundary links*: links connecting boundary nodes belonging to different clusters or DMAs;
  - *internal links*: links connecting boundary nodes belonging to the same clusters or DMAs.

The internal hyper-links represent the connectivity within a cluster (weighted by the strength of their connection), providing information about it after any cluster aggregation process. The weight chosen is the shortest path linking each pairs of boundary nodes belonging to the same cluster, but other approaches are possible (i.e. by considering the diameter and length of pipes).

Following this network decomposition, it is possible to make a MS network related to the original layout but only compressing the items that are key for its connectivity. The aggregation / desegregation of the cluster layout is shown to be straightforwardly simplified by using the MS network associated to the original WDS.

The aggregation process is done by applying semi-supervised clustering [38] running over the MS network and taking into account the boundary nodes membership and internal cluster connectivity as constraints. This structural background knowledge comes in the form of pairwise must-link (boundary links) and cannot-link (internal links) constraints [39]. In this case, the algorithm assures that:

- the new aggregate DMAs include the former districts without splitting them (to better manage the aggregation / desegregation phases);
- the previous cluster layout and the assets already installed are considered (to minimise / nullify new investment costs);
- the set of new boundary links is included in the set of boundary links of the original partitioning (to reduce the computational burden of the whole procedure)

MS network of the original WDS implicitly considers the structural knowledge and simultaneously respects constraints, without the necessity to build further vector or matrix features. Indeed, after the size reduction provided by the MS algorithm, each cluster of the MS network becomes a fully connected layout (whose links are the *internal links*) connected to each other by fewer links (*boundary links*). Thanks to this topological property, the clustering algorithm is assured to always provide a solution in which the novel set of boundary links is a sub-set of the boundary links of the original cluster layout. On top of this, a network community detection algorithm [40] splits a network in such way that each cluster is formed by elements having a high-density connection between each other and a lower probability to be connected to items belonging to other clusters. According to this criterion, the new cluster layout will certainly cross the former boundary links and will not split the original DMAs.

Finally, the community detection algorithm introduced by [41] (based on the search of the edges (links) that are most "between" communities) is used. Girvan-Newman defines the edge betweenness $bc(l)$ of an edge l as the number of shortest paths between pairs of nodes that run along it, in order to find which edges in a network are most between other pairs of nodes. In view of this aspect, pipes between communities are characterised by the high value of the edge betweenness $bc(l)$, since all the shortest paths from one community to another have to pass through them. By removing these edges, the communities are separated one from another.

2.2. Optimisation objectives: recovered energy and leakage reduction

The combination of WDS partitioning with DMAs reduces the overall energy consumption in the system when compared with a completely open WDS. However, this is a global result and it occurs that certain elements, such as the boundary- pipes between DMAs, gain local energy with respect to their associated energy in the completely open WDS. This is one of the main features for harvesting energy at specific points of the WDS. This is added to the better monitoring and control benefits of the WDS management via DMAs.

The clustering phase for the WDS partitioning provides size and shape of each cluster, and the set of boundary link N_{ec} between them (the set of pipes along which gate valves and flow meters must be installed). If N_{fm} is the number of flow meters, then the number of gate valves (e.g. closed pipes) $N_{gv} = N_{ec} - N_{fm}$. The number of all the possible dividing configurations N_{dc} is expressed by the binomial coefficient at the Equation (1):

$$N_{dc} = \binom{N_{ec}}{N_{fm}} = \frac{N_{ec}!}{N_{fm}!N_{gv}!} \tag{1}$$

Due to the large number of possible configurations, a heuristic optimisation approach was adopted to find the optimal positions of flow meters and gate valves on the boundary links. In this case, a Genetic Algorithm (GA) [42] was developed and specifically tailored for this problem.

In this paper, the management of the WDS was split in two main temporal parts, Day (from 6 to 24, to maximise the potentially recovered energy) and Night (from 24 to 5, to better manage pressure and reduce water leakage). According to these main goals of the dynamic DMAs management, two different Objective Functions (OF) were maximised:

$$E_{rec} = 9.8\eta \sum_{j=1}^{n_{PAT}} \sum_{i=6}^{24} q_{j,i} h_m \Delta t \tag{2}$$

Equation (2) corresponds to the potentially recovered energy E_{rec} (kWh) for the Day phase, where η is the mechanical efficiency, $q_{j,i}$ is the hourly flow through the j-th PAT (m^3/s), n_{PAT} is the number of installed PAT, Δt (unity), because hourly simulations were carried out, h_m (m) is the head drop through a micro-PAT.

Modelling a micro-PAT along a pipe provide the means to compute the dissipated energy in such a device which is equal to the potentially recoverable energy. In EPANET [43], the head drop h_m (m) through a micro-PAT can be computed by the equation of the minor head losses through the pipe on which micro-PAT is installed [44]; it can be written in terms of the flow rate $q_{j,i}$ and the valve/pipe diameter D_j [45]:

$$h_m = K_m \frac{8}{\pi^2 g} (\frac{q_{j,i}}{D_j^2})^2 \tag{3}$$

where K_m corresponds to the minor loss coefcient (the higher K_m, the higher the head drop and thus the potentially recoverable energy). In the first optimisation step, the value of K_m was assumed constant for all the PAT.

The novel idea of this dynamic framework is to locate, in the same monitoring stations, both flow-meters and micro-PATs, which further simplifies the system management and reduces the investment cost. In this way, the optimal position of flow-meters (which is generally carried out by minimising the hydraulic performance deterioration) is shifted to find the most adequate site for the micro-PAT scheme which maximises the potential for recovered energy.

To further maximise the management efficiency, a refinement of the optimal solution is carried out by searching for the optimal value of the minor loss coefficient K_m using GA. Such optimisation problem can be mathematically described through Equation (3) in which h_m varies according to the variation of K_m. The value of K_m was inferred from a conventional needle valve chart (Figure 4).

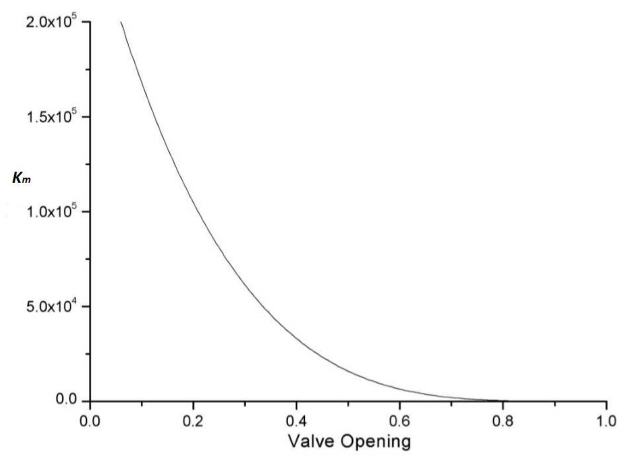


Figure 4: Resistance coefficient for needle valve used in simulations

The minor headloss coefficient initially attributed to all the PAT is $K_m = 1000$; in this subsequent refinement phase, it is varied with a step of 500.

For the Night phase, the leakage reduction function (%) was maximised:

$$L_{red} = (\frac{q_{leak,N} - q_{leak,N^*}}{q_{leak,N}}) * 100 \quad (4)$$

physical loss was concentrated in one node (*emitter*) in the northern part of the WDS; $q_{leak,N}$ is the leakage flow during the Night phase in the the original WDS, while q_{leak,N^*} is the leakage flow during the Night phase in the managed WDS. Leakage was modelled through nodal emitters, using the orifice equation $q_{leak} = k\sqrt{h}$ [46, 47], in which k $(l/s/m^{0.5})$ is the emitter coefficient representing the flow (l/s) that occurs at a pressure drop of 1 m (in this case study $k = 1$, simulating a round nozzle for the occurrence of a leak). h (m) represents the pressure head.

The GA was carried out with 200 generations of a population consisting of 50 individuals. Each individual of the population is a sequence of a number of binary chromosomes equal to the number of boundary links N_{ec} and corresponding to them. Each chromosome assumes value 0 if a gate valve is inserted in the j-th pipe, value 1 otherwise if a flow meter/micro-PAT is installed. The crossover percentage is settled $P_{cross} = 0.8$, and the mutation rate $P_{mut} = 0.02$. The optimisation was done by linking the EPANET hydraulic simulator [43] and the programming language Python 3.7.

2.3. Constraints

Two types of optimisation constraints were considered for both Day and Night phases:

a) satisfaction of hydraulic performance of the system;

b) management simplification and cost reduction

Regarding the first group, the OFs defined in subsection 2.2 are constrained by equations (5) and (6), which imposes a minimum service level for all the users and a minimum resilience to the WDS, respectively:

$$h_{min} \geq h^* \quad (5)$$

where h_{min} is the minimum nodal head pressure, and h^* is the design pressure head of the network (i.e. the minimum required pressure to guarantee the minimum service level to the users).

$$I_r = \frac{\sum_{i=1}^{n_n} Q_i(h_i - h^*)}{\sum_{r=1}^{n_r} Q_r H_r - \sum_{i=1}^{n_n} Q_i h^*} > I_r^* \tag{6}$$

where I_r is the resilience index [48], n_n is the number of demand nodes, n_r is the number of reservoirs, Q_i and h_i are respectively the water demand and the pressure head of the i-th node, Q_r and H_r are the water discharge and the total head of the generic r-th source point. I_r^* is the minimum resilience value fixed for the WDS.

For the second group of constraints, the number of flow-meters N_{fm} were kept as low as possible, since, the smaller the number of flow-meters, the simpler the water budget computation and the WDS management [49]. This aspect also leads to a reduction of the investment cost, as better shown in the following subsection. Finally, the passage from the Day to Night phase is carried out by a further selection of the partitioning configurations that completely consider the assets already installed over the WDS. Thus, the optimal device placement for the Day phase (with 4 DMAs) are preserved also for the Night phase. It allows to speed up the computational operation for finding out the optimal solution (by reducing the possible dividing configurations N_{dc}), and to simplify the management of the WDS.

2.4. Financial Analysis.

The financial feasibility analysis aims to determine whether the balance of costs and savings/benefits of a project is attractive. The adopted model considers year 0 as the initial investment year and the occurrence of an annual cash flow at the end of the year. In this work, a preliminary financial analysis was carried out by including the following factors:

- *investment cost*, micro-PAT cost C_{PAT}, flow-meter cost C_{fm}, gate-valve cost C_{gv}, civil work cost C_{cw};
- *annual cost*, maintenance cost C_m;
- *annual income*, it depends on the leakage reduction (so on the water costs C_w) and on the recovered energy (so, on the electricity selling price C_e).

Civil work cost C_{cw} was estimated at 30% of device costs (20% if flow-meters and micro-PAT are installed in the same monitoring station); maintenance cost C_m was estimated at 10% of total installation cost (sum of all device costs and civil work cost).

A cash-flow analysis during the first 10 years is carried out (this was considered a reasonable time period to evaluate investment by a water company). The investment costs were actualised to the year 0 through the depreciation rate:

$$r_d = \frac{r(1+r)^t}{(1+r)^t - 1} \tag{7}$$

where t is the number of years considered, and r the discount rate.

According to the above-mentioned factors, the Annual Net Income (ANI) was defined:

$$ANI = C_w W_{red} + C_e E_{prod} - r_d * [\sum_{j=1}^{n_{PAT}} C_{PAT} + \sum_{f=1}^{n_{fm}} C_{fm} + \sum_{g=1}^{n_{gv}} C_{gv} + \sum_{c=1}^{n_{fm}} C_{cw}] - \sum_{m=1}^{n_m} C_m \tag{8}$$

where W_{red} is the annual water leakage reduction, E_{prod} is the annual recovered energy potential. The product of C_w and W_{red} is the annual water benefit B_{water}, while the product of C_e and E_{prod} is the annual energy benefit B_{energy}.

The assessment of the cost of water C_w, of selling price of energy C_e, and discount rate r (which can be considered as the opportunity cost of capital) are fundamental for the evaluation of the annual income produced by leakages reduction and recovered energy.

In this paper, constant values for C_w, C_e, r were utilised, making reference to the values reported in [34] for Italy. The unit cost of micro-PAT is estimated as a function of installed kW, as reported in [50]. Table 1 shows the values adopted in this paper.

Table 1: Cost of water C_w, selling price of energy C_e, discount rate r, and unit cost for micro-PAT C_{PAT}

C_w	C_e	r	C_{PAT}
[€/m^3]	[€/kWh]	[-]	[€/kW]
0.300	0.220	0.0542	1200

In Table 2 the average cost of flow-meters and gate-valves are reported according to the diameter of the pipe on which they will be installed.

Table 2: Unit cost of flow-meters and gate-valves as function of the diameter

Diameter	60	80	100	125	150	200
	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]
Flow-meter [€]	1693	1727	1771	1864	1940	2244
Gate-valve [€]	107	130	161	251	274	407

After the final optimal solution is defined, which maximises ANI, the optimal investment period (the time on which it is worthy to invest for a water utility) is computed. This is defined as the period ranging between the year on which the ANI becomes positive and the year on which the increment of ANI becomes less than 10%. The analysis was done by varying the number of years t (from 1 to 20 years) in the depreciation rate r_d of the cash-flow analysis.

The overall process of the proposed management framework is summarised in Figure 5.

3. Case study

The methodology described above was tested on the WDN of Parete [51], a small town located in a densely populated area of the South of Italy, with population of around 11,000 inhabitants. This WDN is constituted by 182 demanding nodes (with ground elevations ranging from 53 m a.s.l. to 79 m a.s.l.), 282 pipes and 2 sources with fixed head of 110 m a.s.l. A uniform

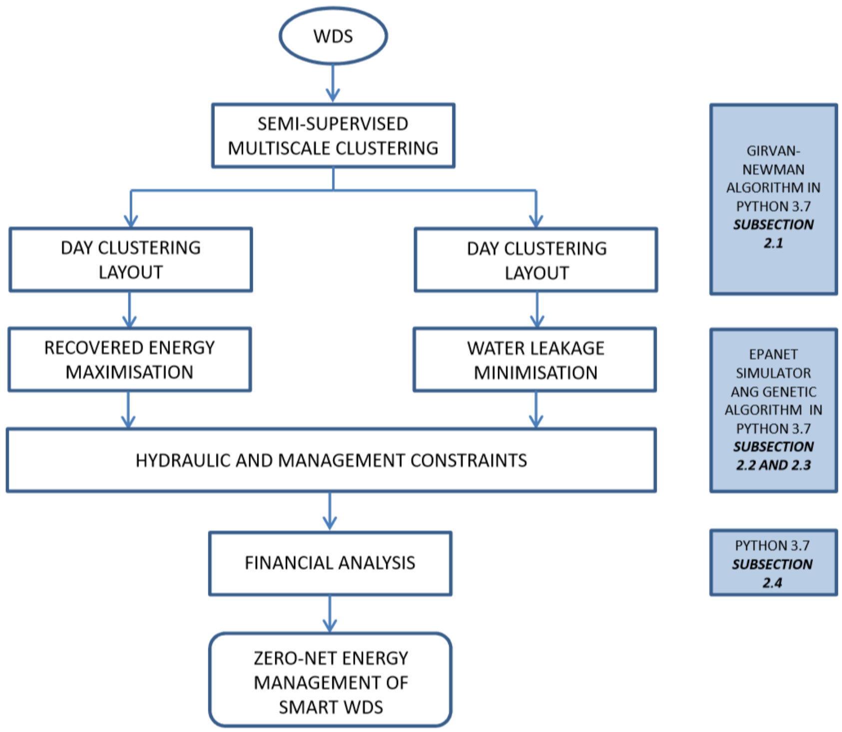


Figure 5: Flowchart of the study

design pressure head $h^* = 19$ m was assumed for the demanding nodes (equal to the sum of the maximum building height in the town, 9 m, and 10 m, as prescribed by the Italian guidelines). The value of the minimum resilience $I_r^* = 70\%\ (I_r, min) = 70\%\ (0.679) = 0.475$ is fixed, where (I_r, min) is the minimum resilience index during the day of the un-partitioned WDS. Reference was made to the day of maximum consumption in the year when the total nodal demand ranges from 14.1 l/s at night time to 83.2 l/s in the morning and midday peaks, with an average value of 58.3 l/s. The leakage volume of the networks in the day of maximum consumption adds up to 553 m^3 (about 11% of the total outflow from the sources). For the analysis, leakage flow was split in two rate: a) $q_{leak,N} = 121.12\ m^3$ during the Night phase, and b) $q_{leak,D} = 431.78\ m^3$ during the Day phase. All the pipes are assumed to feature a Darcy-Weisbach roughness coefficient of 0.85 mm (typical value for cast iron), the diameter ranging from 60 mm to 200 mm and the length from 10.4 m to 542.3 m.

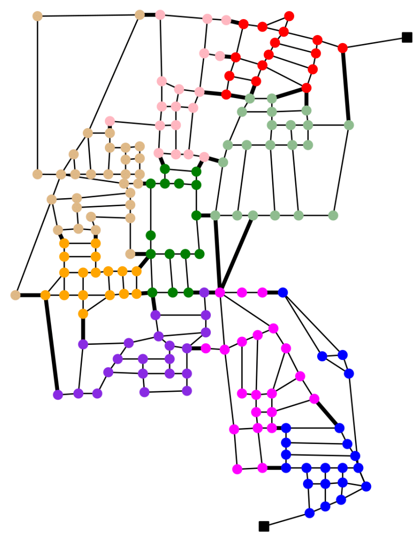
A pattern was used for the hourly demand multiplier to represent the daily variation in the users' demand in the system (with multiplier values ranging from 0.20 to 2.10).

4. Results

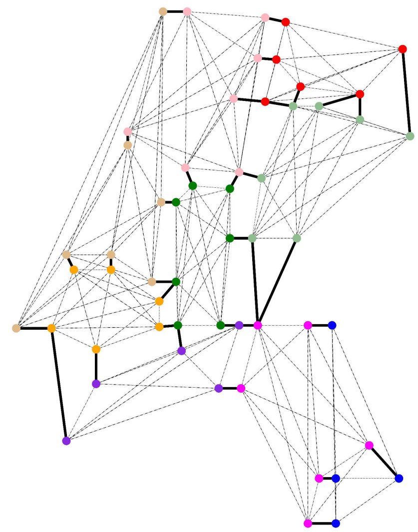
The first step was to define the clustering layout for the Night and Day phases according to the novel dynamic MS framework. The WDS of Parete was clustered in $C = 9$ DMAs during the Night phase (see Figure 6a); the number of boundary links $N_{ec} = 33$. After that, the corresponding MS network is built. Figure 6b shows the size reduction of the Parete WDS after its transformation into a MS network, and the key elements: a) boundary nodes of each cluster (highlighted by their corresponding DMA colour), boundary links (bold black line), and internal links (thin dashed grey line).

For the Day phase, the number of clusters for Parete WDS was set to $C = 4$ (see Figure 6c). The first step of the proposed methodology was to aggregate the previous DMAs in the MS network. The Girvan-Newman algorithm was applied to the MS network to provide the new clustering layout which suitably balances the new bigger 4 DMA (in terms of number of nodes) and minimises the number of boundary links between clusters. These are two crucial aspects for the definition of the new clustering configuration, since they ensure better management (district with same size), reduce the computational burden in the subsequent dividing phase (a lower number of boundary links N_{ec} reduce the number of dividing configuration N_{dc}, as evident by Equation (2)), and reduces the device costs.

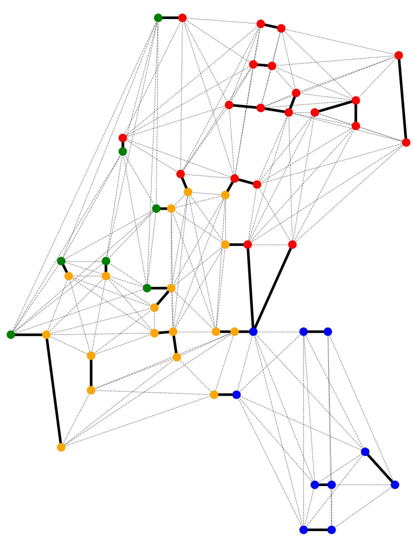
Figure 6d shows that the 4 new, bigger clusters perfectly include the entirety of the former clusters within the new network partitioning (without splitting them). The new set of boundary links $N^*_{ec} = 14$ constitutes a subset of the previous set $N_{ec} = 33$ for the configuration $C = 9$ DMAs. This feature of



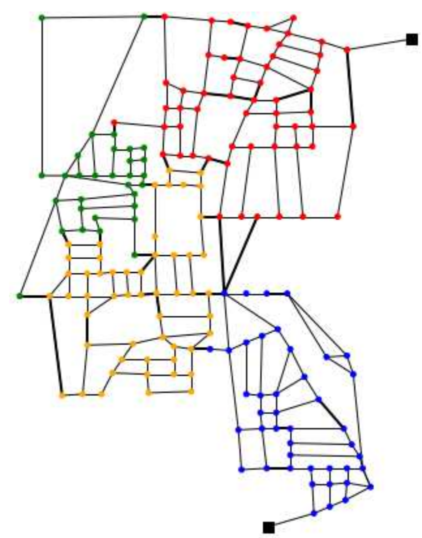
(a) 9 DMAs for Parete WDS during the Night phase



(b) MS layout for 9 DMAs



(c) MS layout for 4 DMAs



(d) 4 DMAs for Parete WDS during the Day phase

Figure 6: Graphical explanation for the creation of Parete MS layout

the dynamic aggregation / desegregation process ensures that the DMAs in each phase are kept in control, using the physical-assets already installed in the WDS.

The optimisation of the device placement was carried out after the definition of the optimal clustering layouts for both Night and Day phases. The results of the dividing step for the Day phase are reported in Table 3, in which the dividing solutions are listed from $N_{fm} = N_{PAT} = 6$ to $N_{fm} = N_{PAT} = 14$. Layouts with a number of $N_{fm} = N_{PAT} < 6$ are not reported since they do not respect the constraints. Values of the un-partitioned network are also reported in the first row.

Table 3: Optimal partitioning solutions for the Day phase; number of boundary pipes N_{ec}, number of flow-meters/PAT N_{fm}, number of gate-valves N_{gv}, recovered energy E_{rec}, water leakage $q_{leak,D}$, minimum resilience index $I_{r,min}$, minimum pressure h_{min}

N_{ec} [-]	N_{fm} [-]	N_{gv} [-]	E_{rec} [kWh]	$q_{leak,D}$ [m^3]	$I_{r,min}$ [-]	h_{min} [m]
-	-	-	0.00	431.77	0.68	26.87
14	6	8	43.54	366.20	0.48	20.58
14	7	7	43.02	378.01	0.49	19.36
14	8	6	43.20	377.57	0.49	19.16
14	9	5	43.36	379.34	0.49	19.06
14	10	4	43.41	380.06	0.49	19.03
14	11	3	39.39	385.02	0.51	20.15
14	12	2	39.29	384.44	0.51	20.04
14	13	1	35.72	389.04	0.51	21.06
14	14	0	35.39	389.03	0.52	20.89

As evident in Table 3, all the listed solutions satisfy the hydraulic constraints, and are suitable for an efficient WDS management. Further, the financial analysis is carried out (see Table 4) to define the most economic option. The layout with $N_{fm} = N_{PAT} > 10$ showed a negative ANI, so they are not valid solutions from an economical point of view. For this case study, for the Day phase, the dividing layout with $N_{fm} = 6$ was chosen as the best one, which simultaneously maximised the ANI and minimised the number of flow-meters N_{fm}), but the water utility could choose any of the other solutions in the range $6 < N_{fm} =$

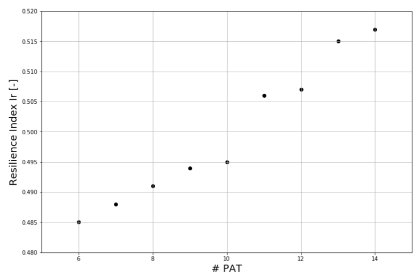
$N_{PAT} < 10$, to suit specific needs.

Table 4: Financial analysis for the optimal partitioning solutions for the Day phase (C=4 DMAs); number of flow-meters/PAT N_{fm}, total cost of PAT, total cost of flow-meters, total cost of gate-valves, civil work cost, maintenance cost, annual energy benefit, annual water benefit, annual income

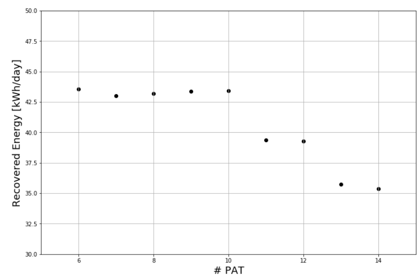
N_{fm} [-]	C_{PAT} [€]	C_{fm} [€]	C_{gv} [€]	C_{cv} [€]	C_m [€/year]	B_{energy} [€/year]	B_{water} [€/year]	ANI [€/year]
6	7200	12079	1131	4195	2460	3496	7180	4964
7	8400	13559	1168	4742	2786	3454	5887	2871
8	9600	15330	1007	5288	3122	3469	5935	2155
9	10800	17023	900	5834	3455	3482	5741	1200
10	12000	18716	793	6381	3789	3486	5662	352
11	13200	20580	542	6918	4124	3163	5119	-1292
12	14400	22351	381	7464	4459	3155	5183	-2016
13	15600	24213	161	8010	4798	2869	4678	-3593
14	16800	25984	0	8556	5134	2842	4680	-4397

In Figure 7, the relationship between the different parameters were also investigated. As expected, the resilience index I_r increases as the number of flow-meters/PAT increases (Figure 7a) resulting in a less dissipation of hydraulic energy. On the contrary, the potentially recovered energy shows a decreasing trend with the number of flow-meters/PAT (Figure 7a). This could be due to the fact that, the lower the number of open connections between districts, the higher the value of hourly water flow $q_{j,i}$ along them, and as a consequence, the higher the value of recovered energy (see equations (2) and (3), in which the water flow is raised to the power of one and two, respectively). Regarding the water leakage, the higher the number of flow-meters/PAT, the lower its reduction (see Figure 7c), since the head drop caused by the micro-PAT is lower than that caused by the complete closure of pipes. Due to the previous decreasing trends of potentially recovered energy and leakage reduction, ANI itself showed a decreasing trend reaching its maximum value for $N_{fm} = 6$ (Figure 7d).

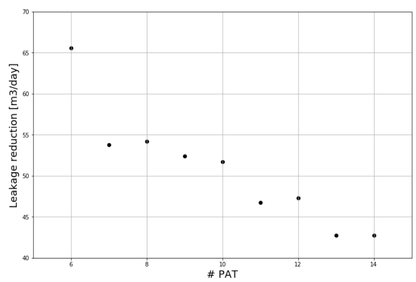
Figure 8a shows the trend between leakage reduction and recovered energy; reduction of leakage resulted in maximum energy recovery. The trade-off between the resilience index and the recovered energy (see Figure 8a) led to a



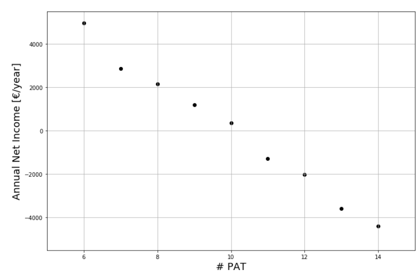
(a) Resilience index VS Number of PAT



(b) Recovered energy VS Number of PAT



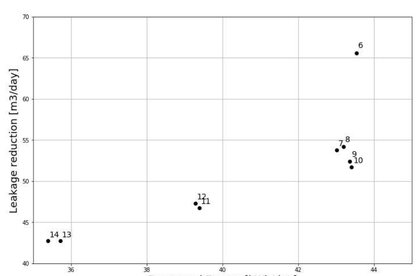
(c) Leakage reduction VS Number of PAT



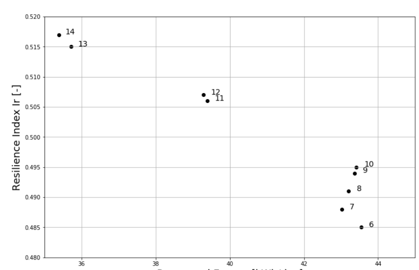
(d) Annual net income VS Number of PAT

Figure 7: Relationship between performance parameters and number of installed PAT

non-univocal choice for the optimal management solution, further justifying the use of the financial analysis.



(a) Leakage reduction VS Recovered energy



(b) Resilience index VS Recovered energy

Figure 8: Relationship between performance parameters

The refinement of the adopted dividing layout for the Day phase (N_{fm} = N_{PAT} = 6), was carried out to further recover energy and reduce leakage. For 2 of the 6 micro-PAT (located in the Northern part of the WDS in which the pressure head were much more higher than the design pressure h^*), the minor loss coefficient was set $k_m = 2000$. Results are reported in Table 5, the second row reports the difference in percentage with respect to the solution with k_m = 1000 for all the micro-PAT.

Table 5: Performance after the optimisation of the minor loss coefficient for the dividing layout with $N_{fm} = N_{PAT} = 6$ during the Day phase; recovered energy E_{rec}, water leakage $q_{leak,D}$, minimum resilience index $I_{r,min}$, minimum pressure h_{min}, Annual Net Income ANI

E_{rec} [kWh]	$q_{leak,D}$ [m^3]	$I_{r,min}$ [-]	h_{min} [m]	ANI [€ /year]
46.14	361.95	0.48	19.46	5638
+ 5.9%	− 1.3%	− 1.4%	− 5.4%	+ 13.6%

Next was the definition of the optimal dividing layout for the Night phase (9 DMAs). The number of boundary pipes are $N_{ec} = 33$; for 14 of them, the optimal device positioning is already defined in the Day phase ($N_{fm} = N_{PAT}$ = 6, and $N_{gv} = 8$). The first attempt was to close all the new boundary pipes and check the hydraulic performance. Since the hydraulic constrains were not satisfied, a new optimisation was carried out according to the Equation (4) focusing only on $N_{ec,red} = N_{ec}$ - N^*_{ec} = 33 - 14 = 19 boundary pipes. Due to the low value of the water flow during the Night phase, no other micro-PAT was adopted (since the potentially recovered energy would be very low). The optimisation only defines which pipes are closed and which of them are left open. After that, for the micro-PAT already installed during the Day phase, the optimisation of the minor loss coefficient is carried out.

Table 6 reports the results of the simulations; the number of assets that are located with the optimisation of the Night phase, for which the financial analysis is done, are shown in parentheses (Table 7). The value of the minor loss coefficient after the refinement is $k_m = 1500$ (for 4 micro-PAT), and k_m = 2500 (for 2 micro-PAT), following the same layout defined for the Day phase.

Table 6: Optimal partitioning solutions for the Night phase (C=9 DMAs); number of boundary pipes N_{ec}, number of flow-meters N_{fm}, number of gate-valves N_{gv}, recovered energy E_{rec}, water leakage q_{leak,N^*}, minimum resilience index $I_{r,min}$, minimum pressure h_{min}

$\boldsymbol{N_{ec}}$	$\boldsymbol{N_{fm}}$	$\boldsymbol{N_{gv}}$	$\boldsymbol{E_{rec}}$	$\boldsymbol{q_{leak,N^*}}$	$\boldsymbol{I_{r,min}}$	$\boldsymbol{h_{min}}$
[-]	[-]	[-]	[kWh]	[m^3]	[-]	[m]
33(19)	10(4)	23(15)	5.22	101.09	0.52	19.15

Table 7: Financial analysis for the optimal partitioning solutions for the NIGHT phase (C=9 DMAs) for the WDN of Parete; total cost of flow-meters C_{fm}, total cost of gate-valves C_{gv}, civil work cost C_{cv}, maintenance cost C_m, annual energy benefit B_{energy}, annual water benefit B_{water}, annual income ANI

$\boldsymbol{C_{fm}}$	$\boldsymbol{C_{gv}}$	$\boldsymbol{C_{cv}}$	$\boldsymbol{C_m}$	$\boldsymbol{B_{energy}}$	$\boldsymbol{B_{water}}$	$\boldsymbol{ANI}$
[€]	[€]	[€]	[€ /year]	[€ /year]	[€ /year]	[€ /year]
8199	2882	3324	1441	420	2193	-731

Table 8 lists the cost/benefit for the Day and Night phases; the total Annual Net Income for the adopted solution is $ANI =$ €4906.

Table 8: Financial analysis for the optimal partitioning solution; total annual net income, total cost and annual energy and water benefits during the Day phase, total cost and annual energy and water benefits during the Night phase

ANI	Day			Night		
	C_{TOT}	B_{energy}	B_{water}	C_{TOT}	B_{energy}	B_{water}
[€ /year]	[€ /year]	[€ /year]	[€ /year]	[€ /year]	[€ /year]	[€ /year]
4906	5712	3705	7645	3344	420	2193

Finally, by varying the investment year from $t = 1$ year to $t = 20$ years, the optimal payback period for the adopted partitioning layout is defined. Results are plotted in Figure 9; labels report the percentage of relative increment between two consecutive years.

The trend of the ANI starts with negative values and increases as the investment period becomes longer. From $t = 5$ years, it is worthy to invest (since $ANI > 0$). According to the adopted criteria (time to which the increment of ANI becomes less than 10%), the upper bound for the investment period is $t =$ 10 years (increment of ANI is 12.2% for $t = 9$ years and 8.9% for $t = 10$ years).

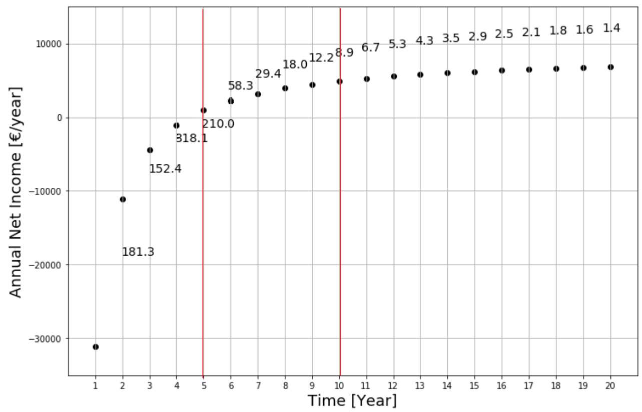


Figure 9: Optimal payback period analysis

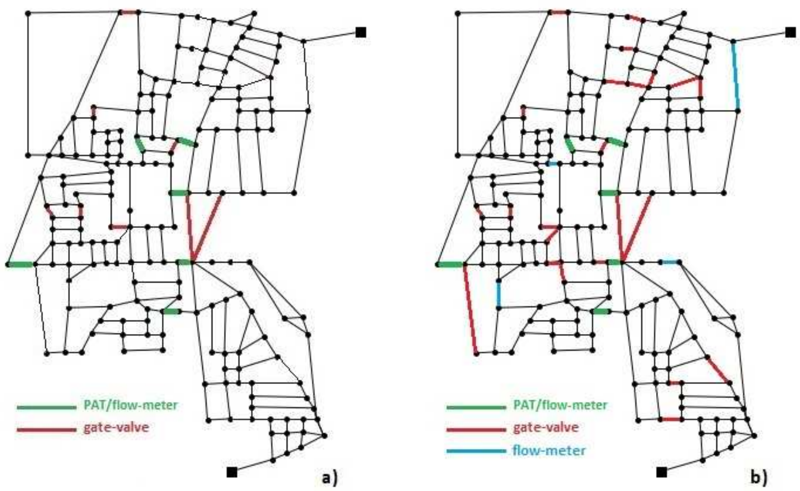
Figure 10a and Figure 10b report the optimal partitioning layout for the Day and the Night phases, respectively. The boundary pipes (and the installed assets) of the former layout constitutes a sub-set of the boundary pipes of the latter. This constitutes an efficient and sustainable management strategy which simplifies network monitoring and maintenance. In fact, only the opening/closure of some pipes is required (15 gate-valves) and the setting of the 6 micro-PAT from Night to Day phase.

With the proposed MS layout and the installation on the same monitoring stations of both flow-meters and micro-PATs, the multiple-use of the partitioning is attained.

5. Discussion

A smart city can be defined as a city in which an investment in human and social capital is performed, by encouraging the use of "Information and Communication Technology" (ICT) as enabler of sustainable economic growth, providing improvements in the quality of life of consumers, and consequently, allowing better management of water resources and energy. This represents the main goal of this work, whose results can be summarised in two group:

- *Technical and computational aspects*:



(a) Optimal partitioning layout for the Day phase (4 DMAs)

(b) Optimal partitioning layout for the Night phase (9 DMAs)

Figure 10: Optimal management strategy for the WDS of Parete

  - the dynamic water network partitioning allows to address different management tasks according to the variability of the conditions of a WDS making the system more adaptive;
  - the installation of micro-PATs and flow-meters in the same stations simplifies the management and reduces the investment and maintenance costs;
  - flow-meters and sensors can be powered through the recovered energy, conferring greater reliability to the monitoring system;
  - the application of the multi-scale layout reduces the computational complexity during the definition of the optimal partitioning and simplifies the aggregation/desegregation of the districts at each level;

- *Environmental and social aspects*:
  - the combined use of water network partitioning and micro-PATs simultaneously permits simplification of the WDS management, re-

duces water leakage, produces green energy;

– the surplus of the recovered energy can be used to power electrical charging stations e.g. for electric cars and mobile phones, or provide streetlighting especially in off-grid areas;

– reducing leakages and recovering energy strongly contribute to reduce CO_2 emissions;

– the smart management of WDSs through multiple-use monitoring stations advances the zero-net cost control of water systems, reduces the economic impact on the water utility budget without negative cost and quality impact on end-users;

All these aspects delivers a Smart Water System (SWS) characterised by smart water management, through the use of innovative information, control and monitoring technologies.

6. Conclusion

This paper takes advantage of a WDS partitioning into DMAs. It is known that energy decreases in a WDS with the creation of DMAs. However, it locally increases (compared to widely open WDS layout) at certain elements such as the boundary pipes between DMAs. These elements are therefore good candidates for locating energy recovery devices. Besides this novel application in network partitioning, the well-known improvement on the monitoring and control of a WDS divided into DMAs was also demonstrated. Both characteristics were proposed in the novel framework of dynamic DMA partitioning based on a multiscale approach for a water network. Dynamic DMAs adapt themselves to a range of scenarios occuring in the water distribution network, boosting both the energy harvesting potential and the monitoring and control of a WDS.

The recovered energy, along some of the boundary pipes between districts, can be used to supply the electrical needs of the station (or water quality sensors). Through effective integrated, only one management strategy is needed to deliver better system control, reduce leakages, recover energy, and monitor water quality, therefore minimising the overall cost, by creating multiple-task monitoring stations along the boundary pipes between each DMA.

References

[1] G. Forzieri, A. Cescatti, F. B. e Silva, L. Feyen, Increasing risk over time of weather-related hazards to the european population: a data-driven prognostic study, The Lancet Planetary Health 1 (5) (2017) 200–208.

[2] T. Luna, J. Ribau, D. Figueiredo, R. Alves, Improving energy efficiency in water supply systems with pump scheduling optimization, Journal of Cleaner Production 213 (2019) 342–356.

[3] IEA, 2016. world energy outlook 2016 - special report: Water-energy nexus, https://webstore.iea.org/weo-2016-special-report-water-energy-nexus.

[4] J. Bere, C. Jones, S. Jones, M. Munday, Energy and development in the periphery: A regional perspective on small hydropower projects, Environment and Planning C: Politics and Space 35 (2) (2017) 355–375.

[5] R. Bhandari, L. G. Saptalena, W. Kusch, Sustainability assessment of a micro hydropower plant in nepal, Energy, Sustainability and Society 8 (1) (2018) 3.

[6] U. Nations, Transforming our world: The 2030 agenda for sustainable development, Resolution adopted by the General Assembly.

[7] C. Giudicianni, A. Di Nardo, M. Di Natale, R. Greco, G. Santonastaso, A. Scala, Topological taxonomy of water distribution networks, Water 10 (4) (2018) 444.

[8] W. M. Grayman, R. Murray, D. A. Savic, Effects of redesign of water systems for security and water quality factors, in: World Environmental and Water Resources Congress 2009: Great Rivers, 2009, pp. 1–11.

[9] M. Housh, Z. Ohar, Model-based approach for cyber-physical attack detection in water distribution systems, Water research 139 (2018) 132–143.

[10] M. Herrera, R. Wright, C. Giudicianni, A. Di Nardo, J. Izquierdo, Complex network multiresolution for optimal sensor placement in big urban infrastructures, Artificial Intelligence Research and Development: Current Challenges, New Trends and Applications 308 (2018) 74.

[11] Y. Wu, S. Liu, X. Wu, Y. Liu, Y. Guan, Burst detection in district metering areas using a data driven clustering algorithm, Water research 100 (2016) 28–37.

[12] J. Gallagher, D. Styles, A. McNabola, A. P. Williams, Life cycle environmental balance and greenhouse gas mitigation potential of micro-hydropower energy recovery in the water industry, Journal of Cleaner Production 99 (2015) 152–159.

[13] K. Urbaniec, H. Mikulčić, M. A. Rosen, N. Duić, A holistic approach to sustainable development of energy, water and environment systems, Journal of cleaner production 155 (2017) 1–11.

[14] P. F. Boulos, A. S. Aboujaoude, Managing leaks using flow step-testing, network modeling, and field measurement, Journal-American Water Works Association 103 (2) (2011) 90–97.

[15] K. Hindi, Y. Hamam, Locating pressure control elements for leakage minimization in water supply networks: An optimization model, Engineering optimization 17 (4) (1991) 281–291.

[16] O. Fecarotta, A. McNabola, Optimal location of pump as turbines (pats) in water distribution networks to recover energy and reduce leakage, Water resources management 31 (15) (2017) 5043–5059.

[17] W. I. R. Ltd, A manual of dma practice, London, UK Water Industry Research.

[18] E. Farah, I. Shahrour, Leakage detection using smart water system: combination of water balance and automated minimum night flow, Water Resources Management 31 (15) (2017) 4821–4833.

[19] G. Ferrari, D. Savic, G. Becciu, Graph-theoretic approach and sound engineering principles for design of district metered areas, Journal of Water Resources Planning and Management 140 (12) (2013) 04014036.

[20] N. Taillefond, O. Wolkenhauer, Fuzzy clustering and classification for automated leak detection systems, IFAC Proceedings Volumes 35 (1) (2002) 407–411.

[21] J. Feng, H. Zhang, Algorithm of pipeline leak detection based on discrete incremental clustering method, in: International Conference on Intelligent Computing, Springer, 2006, pp. 602–607.

[22] S. Chianese, A. Di Nardo, M. Di Natale, C. Giudicianni, D. Musmarra, G. F. Santonastaso, Dma optimal layout for protection of water distribution networks from malicious attack, in: International Conference on Critical Information Infrastructures Security, Springer, 2017, pp. 84–96.

[23] E. Campbell, J. Izquierdo, I. Montalvo, R. Pérez-García, A novel water supply network sectorization methodology based on a complete economic analysis, including uncertainties, Water 8 (5) (2016) 179.

[24] A. Di Nardo, M. Di Natale, R. Gargano, C. Giudicianni, R. Greco, G. F. Santonastaso, Performance of partitioned water distribution networks under spatial-temporal variability of water demand, Environmental Modelling & Software 101 (2018) 128–136.

[25] R. Wright, I. Stoianov, P. Parpas, K. Henderson, J. King, Adaptive water distribution networks with dynamically reconfigurable topology, Journal of Hydroinformatics 16 (6) (2014) 1280–1301.

[26] R. Wright, I. Stoianov, P. Parpas, Dynamic topology in water distribution networks, Procedia Engineering 70 (2014) 1735–1744.

[27] O. Fecarotta, A. Carravetta, M. Morani, R. Padulano, Optimal pump scheduling for urban drainage under variable flow conditions, Resources 7 (4) (2018) 73.

[28] E. Cabrera, E. Cabrera Jr, R. Cobacho, J. Soriano, Towards an energy labelling of pressurized water networks, Procedia Engineering 70 (2014) 209–217.

[29] T. Tucciarelli, A. Criminisi, D. Termini, Leak analysis in pipeline systems by means of optimal valve regulation, Journal of Hydraulic Engineering 125 (3) (1999) 277–285.

[30] L. Araujo, H. Ramos, S. Coelho, Pressure control for leakage minimisation in water distribution systems management, Water resources management 20 (1) (2006) 133–149.

[31] H. Ramos, A. Borga, Pumps as turbines: an unconventional solution to energy production, Urban Water 1 (3) (1999) 261–263.

[32] M. Pérez-Sánchez, F. Sánchez-Romero, H. Ramos, P. López-Jiménez, Energy recovery in existing water networks: Towards greater sustainability, Water 9 (2) (2017) 97.

[33] A. Carravetta, G. Del Giudice, O. Fecarotta, H. M. Ramos, Energy production in water distribution networks: A pat design strategy, Water resources management 26 (13) (2012) 3947–3959.

[34] O. Fecarotta, C. Aricò, A. Carravetta, R. Martino, H. M. Ramos, Hydropower potential in water distribution networks: Pressure control by pats, Water resources management 29 (3) (2015) 699–714.

[35] M. De Jong, S. Joss, D. Schraven, C. Zhan, M. Weijnen, Sustainable–smart–resilient–low carbon–eco–knowledge cities; making sense of a multitude of concepts promoting sustainable urbanization, Journal of Cleaner production 109 (2015) 25–38.

[36] M. Deakin, A. Reid, Smart cities: Under-gridding the sustainability of city-districts as energy efficient-low carbon zones, Journal of Cleaner Production 173 (2018) 39–48.

[37] C. Giudicianni, A. di Nardo, A. Scala, M. Herrera, Multiscale shortest path algorithm for big-size utility networks, arXiv preprint arXiv:1903.11710.

[38] B. Kulis, S. Basu, I. Dhillon, R. Mooney, Semi-supervised graph clustering: a kernel approach, Machine learning 74 (1) (2009) 1–22.

[39] M. Herrera, S. Canu, A. Karatzoglou, R. Pérez-García, J. Izquierdo, An approach to water supply clusters by semi-supervised learning, in: Int. Congress on Environmental Modelling and Software, 5th Biennial Meeting, Ottawa, Canada, 2010, p. 190.

[40] S. Fortunato, D. Hric, Community detection in networks: A user guide, Physics Reports 659 (2016) 1–44.

[41] M. Girvan, M. Newman, Community structure in social and biological networks, Proc. Natl. Acad. Sci. USA 99 (2002) 7821–7826.

[42] D. E. Goldberg, J. H. Holland, Genetic algorithms and machine learning, Machine Learning 3 (2) (1988) 95–99.

[43] L. A. Rossman, Epanet 2, Users manual. US Environmental Protection Agency (EPA), USA.

[44] N. Fontana, M. Giugni, D. Portolano, Losses reduction and energy production in water-distribution networks, Journal of Water Resources Planning and Management 138 (3) (2011) 237–244.

[45] B. Coelho, A. Andrade-Campos, Energy recovery in water networks: Numerical decision support tool for optimal site and selection of micro turbines, Journal of Water Resources Planning and Management 144 (3) (2018) 04018004.

[46] T. Walski, W. Bezts, E. T. Posluszny, M. Weir, B. E. Whitman, Modeling leakage reduction through pressure control, Journal-American Water Works Association 98 (4) (2006) 147–155.

[47] F. D. Paola, M. Giugni, Leakages and pressure relation: an experimental research, Drinking Water Engineering and Science 5 (1) (2012) 59–65.

[48] E. Todini, Looped water distribution networks design using a resilience index based heuristic approach, Urban Water 2 (2) (2000) 115–122.

[49] A. Di Nardo, M. Di Natale, C. Giudicianni, G. F. Santonastaso, V. Tzatchkov, J. M. R. Varela, Economic and energy criteria for district meter areas design of water distribution networks, Water 9 (7) (2017) 463.

[50] A. McNabola, P. Coughlan, A. Williams, The technical and economic feasibility of energy recovery in water supply networks, in: Proceedings of International Conference on Renewable Energy and Power Quality, Las Palmas de Gran Canaria, Spain, Vol. 1315, 2011.

[51] A. Di Nardo, M. Di Natale, C. Giudicianni, G. Santonastaso, D. Savic, Simplified approach to water distribution system management via identification of a primary network, Journal of Water Resources Planning and Management 144 (2) (2017) 04017089.